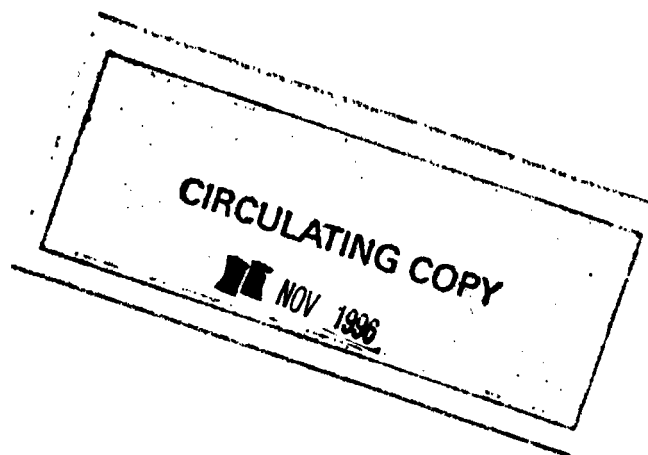ARMY RESEARCH LABORATORY

Strategy and Goals of the Ballistic Vulnerability/Lethality Division Program for the Investigation of Ballistic Shock Phenomena

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13. ABSTRACT *(Maximum 200 words)*

This special report presents an overview of the Ballistic Vulnerability/Lethality Division's (BVLD) ballistic shock program initiated as an in-house mission program at the U.S. Army Ballistic Research Laboratory during 1991. This effort was designed to address BVLD's need for a ballistic shock methodology to incorporate into existing vulnerability models. Current vulnerability assessment models do not handle ballistic shock related damage in a satisfactory manner and since the future trend in armored vehicle development has shown a prevalence for inclusion of shock sensitive electronic components, it is necessary to account for this type of damage mechanism. Hence, there is a need for an improved methodology to fill this void. The current and planned research efforts, rationale, and objectives are presented along with the necessary assumptions needed to incorporate results into analytical tools compatible with current vulnerability models.

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1. BACKGROUND

As the nature of combat has evolved, the tactical requirements for armored vehicles have become more stringent and complex which has led to solutions encompassing technologically advanced components and systems. The incorporation of this type of solution, though, comes with a price. These technologically advanced mechanisms are inherently less robust to mechanical shock. As the battlefield environment has become more severe, armored combat vehicles have become better protected against the standard threats associated with penetration and perforation, but exhibit combat degradation due to shock effects to a greater extent than before. Thus, in terms of overall combat degradation, ballistic shock effects are becoming more pronounced and this trend is expected to continue in the foreseeable future.

To analyze and assess damage due to ballistic shock during full-scale vulnerability testing is relatively straightforward; however, it is quite another matter to be able to model and predict these events within the framework of current vulnerability methodologies. Current vulnerability methodologies predict combat degradation in terms of the physical damage caused by the penetration of the kinetic energy (KE) projectile or chemical energy (CE) warhead and associated behind armor debris (BAD). Current methodology does not address combat damage due to other effects such as fire, toxic fumes and ballistic shock. It is this need and lack of capability that drives the requirement for modifying existing methodologies to address adequately the issue of ballistic shock.

In light of this situation, an in-house research effort was initiated by the U.S. Army Ballistic Research Laboratory (BRL) (now the U.S. Army Research Laboratory, i.e., ARL) during the 1991 timeframe [1]. As outlined in reference 1, the goal of this program was to develop a methodology to assess and predict ballistic shock effects that was suitable for use as an everyday tool for the average vulnerability analyst. It is important to note here that an indispensable goal was to develop a method simple and robust enough to give reasonable answers in a reasonable period of time. Due to the nature of vulnerability analyses, where it is frequently necessary to handle multiple threats at varying mass/velocity combinations at varying attack angles and target locations against various targets, it is pragmatically impossible to utilize solutions that are computationally and manpower intensive, such as finite element models. Though this method and other similar methods may yield an assessment and possibly a better assessment, they are not practical for a variety of reasons. First and foremost, these methods require explicit and detailed data on targets that is not possible to obtain in some instances, e.g., foreign vehicles or prototype U.S. vehicles that have not reached the design stage. Secondly, given the current workload placed upon the typical analyst and the significant cost required to use finite element models, in terms of manpower and computer resources, it is essential that the methodology be simple and practical. A more in-depth and complete rationale is presented in reference 1, which served as a roadmap that guided this research effort from the start.

A brief overview of the vulnerability/lethality process structure, as defined by Walbert, Roach and Burdeshaw [2], and how shock as a damage mechanism fits in, is in order here. The process structure is divided into four spaces consisting of the weapon/target interaction space, the damage space, the reduction of capability space and the utility loss space. The weapon/target interaction space is mapped or transformed to the damage state space by considering the damage mechanisms involved in the process. In addition to the currently considered penetration/ perforation damage mechanisms, another mechanism of consideration could be shock. The mapping from the damage state space to the reduction of capability state space is simply an engineering assessment of the system capability loss when the damage vector is applied. The mapping from the system capability loss state to the utility or measure of effectiveness state is probably the most subjective mapping and is unique for each specific scenario. The last two mappings will not be addressed under the auspices of this program. Thus, it is the mapping from the first state to the second state that is of fundamental interest here and this program will attempt to develop a method to conduct that mapping with respect to shock as the damage mechanism.

2. INTRODUCTION

Shock is generally defined as a relatively large force applied suddenly and quickly with a time period that is relatively short as compared to the natural period of the structure that is being subjected to this force. This transient force can produce damage local to the point of application of this force and also vibratory forces that affect the structure beyond the local point of application. These nonlocal effects are called the global effects and comprise the focal point of this research effort.

Due to the constraint that the methodology be relatively simple to use (though not necessarily to develop), a multifaceted approach was chosen to minimize the overall program risk and to evaluate the different techniques that have been developed to address ballistic shock effects. It was not known *a priori* which, if any, methods would be suitable for inclusion into current vulnerability methodologies. Suitability is defined here in terms of giving reasonable answers while being used as an everyday tool by any vulnerability analyst. The question as to what is reasonable is very subjective and depends on the application. All methods developed will be assessed empirically in this sense and therefore a criterion for what is reasonable can not be explicitly stated at this time. The program, as stated in reference 1, essentially consists of four parts.

(1) Determining the spectra of loading functions of interest in a manner suitable for inclusion in the developing techniques.

(2) Determining the specific response of the structure of interest with respect to the loading functions.

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(3) Correlating the structural response to some type of component or system failure, or specific loss of function and also correlating the structural response to structural failure.

(4) Incorporating the methodology into an existing analysis environment such as the Modular Unix-based Vulnerability Estimate Suite (MUVES).

Delineating the program into these four parts allows for a natural and logical division of labor with the ability to investigate each one of these objectives separately and to assign risk.

When this program was started in 1991, part 1 was assigned to the former Terminal Ballistic Division (TBD) of BRL since the derivation of loading functions was one of their secondary tasks. Part 1 was scheduled to be completed by the end of FY93. Due to coordination conflicts this task was reassigned under contract DAAA15-92-K-0001 [3] to the University of Dayton Research Institute (UDRI). The risk assigned to this part was medium.

Part 2 of the program was considered to be the main thrust of this effort and was assigned to an ARL team comprised of the authors of this report. By the end of FY93 the *qualitative* response of *simple* structures to various induced loadings was to be determined. This part was investigated in a number of different ways, but, in essence, consisted of three analytical techniques and an empirical technique.

Part 3 is scheduled to be completed by the end of FY94 (which in hindsight looks optimistic by about a year) and is currently assigned to the authors of this report. This objective is considerably more difficult, both conceptually and mathematically, than the others and is rated as a high risk. The first area of consideration will be to develop "rules of thumb" for qualitative damage (to include personnel) and then to attempt to quantify some shock failure criteria for generic components in armored vehicles based on quantitative shock loadings.

The fourth part is probably the easiest goal to address since it just requires some straightforward effort once the methodology concepts and mathematics are developed for the first three parts. Part 4 is scheduled to be completed by the end of FY94 and is considered a medium risk, more so due to the schedule than the technical complexities. This tasking has not been assigned, but is expected to be an in-house project. As a corollary effort to this goal, a contract was let with The SURVICE Engineering company to provide visualization software to show shock levels on the skin of a target as a function of time. More specifically, the ARL team will provide the shock algorithm to SURVICE for inclusion within software which SURVICE develops.

This has been a very general synopsis of the overall shock program and the subsequent sections will explain in more detail the specific approaches investigated, the current status of all tasks and the future efforts as envisioned by the ARL shock methodology team.

3. DETAILS

3.1 LOADING FUNCTIONS

As mentioned previously, the development of loading functions that represent shock due to ballistic impacts was contracted to the UDRI after BRL put out a Broad Area Announcement (BAA). A number of firms submitted proposals of which UDRI's appeared to align most closely with our objectives. The contract and UDRI's proposal [3] actually stipulate that they will develop a methodology to address shock effects on armored targets, not just loading functions. We are primarily interested in the analytical loading functions that need to be developed in any case, but their proposal has considerable technical merit and will be presented next.

UDRI's basic premise is that a finite element model can be built for a vehicle and a modal analysis performed *only once* to determine the natural frequencies, vibration mode shapes, and the modal forces/stresses of the vehicle. Once the modal analysis is completed, the response of the structure to forcing (loading) functions can be determined easily by integrating the modal equations of motion. The results consist of modal amplitudes as a function of time which can be scanned to find the critical stress conditions. What makes this approach appear to be feasible at this time is that the structural response can be broken down into global and local responses. The local response is the "localized" modes of failure relative to the impact point due to the penetration and spall effects associated with such events. The global response is the "nonlocalized" modes of failure associated with the global deformation waves or the wave motions transmitted between the components or substructures of the vehicle. The key to this distinction is that the difference between the global and local responses can be characterized in terms of the frequency content where the local impact response consists of high frequency wave motions while the global response is dominated by the low frequency components of the structural response. Thus, it is possible to model the global response (the interest of this program) with just the first few lowest frequency mode shapes. Once the modal analysis is performed, only a limited number of mode shapes and amplitudes are necessary to model the response to specific loading conditions thereby limiting the computational and personnel effort to make this approach feasible. There are a number of drawbacks to this method. First, a finite element model of each target is needed, and, in some cases, as mentioned previously, this will not be possible due to lack of data; and second, the answers will only be as good as the finite element model which requires an expert to build *and interpret* the results and this method still requires more effort than desired. This task is expected to be completed in FY94 using very simple geometries such as flat plates and combinations thereof.

A primary goal of this contract, from ARL's perspective, is the development of analytical loading functions validated computationally and empirically that represent a range of impacts of interest. The velocity range of interest for KE type impacts is 1 km/s to 3 km/s and for jet velocity type impacts the value is approximately 8 km/s. For the KE impacts a tungsten rod (L/D of 10) was used at four test conditions with three replications for a total of 12 shots. For validation of the CE impacts, a 1-gram tungsten sphere will be fired at 7 km/s to closely match the Hugoniot

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for pressure exerted by the CE impacts. This also will consist of 3 replications of 4 test conditions for a total of 12 shots. This experimental data will be used to adjust the hydrocode model (research version of EPIC-2) of the penetration process which is used to calibrate the analytical loading function.

There are essentially two methods used to derive loading functions; a hydrocode estimation of the pressure exerted by the projectile during the penetration process and a mathematical description of the loading function based on conservation of momentum principles. Both methods will be used here. The proposed analytical loading function is presented below.

$$F(r, t) = F_o(t) e^{(-\frac{1}{2}) (\frac{r}{s})^2} \tag{1}$$

where r = radial distance from impact point
t = time
s = standard deviation assumed to be 1/3 cavity radius
$F_o(t)$ = maximum pressure (stress) amplitude

This analytical loading function, based on a conservation of momentum approach, represents the stress as a Gaussian function of the radial distance from the point of impact. The hydrocode calculations will be used to generate correction coefficients to the momentum transfers implied by this equation. In this manner it is expected that loading functions will be developed and validated which will not only be useful for this contractual effort but will have equal utility as forcing functions for the subsequent methods proposed in this report.

3.2 STRUCTURAL RESPONSE

As mentioned in the introduction, determination of the structural response was considered to be the most technically challenging objective, mainly due to the constraint that the resulting methodology be labor and computer nonintensive, and thus, comprised the main thrust of this program. Objective 1 was considered to be relatively straightforward with no insurmountable technical obstacles. Objective 4, primarily a programming effort, was also considered technically straightforward, though not necessarily easy. Objective 3 is probably the most difficult task from a conceptual viewpoint, however, it is perceived that if objective 2 can be satisfactorily addressed then some type of correlation can be implemented to satisfy objective 3. The question then becomes, "How satisfactory, i.e., precise, is the correlation?" This can not be answered until objective 2 is investigated. With the constraint that the techniques or methods developed for objective 2 be computer and personnel nonintensive, the following methods were investigated. It should be stated here that the methods presented next are not prioritized in any manner and no inferences as to their technical merit and applicability should be construed from the order of presentation.

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Before delving into the details of each avenue of approach to investigate structural response, it must be stated that the various approaches were chosen on the basis of their suitability to achieve this objective under the time and resource constraints previously mentioned. They were not chosen to compliment one another or fit into any preconceived ideas of what the methodology should be. Because of this, the approaches are very dissimilar in general, though they may complement each other in some specific instances. For example, it is thought at this time that the rigid body method might be suitable for crew casualty assessments and extreme structural damage estimates, while the shortest path method would be more applicable for moderate structural damage and component failure. These beliefs have not been validated yet, but that will happen during the analysis phase of the experimental test on the real vehicles. Thus, it would be premature at this time to explicitly state a definitive position on how each method utilized for determining structural response ties together. It is entirely possible that only one of the methods might be chosen for inclusion into the methodology and the rest discarded, or more likely, that some combination of the succeeding methods be used.

3.2.1 RIGID BODY METHOD

The rigid body method treats the structure as a rigid body or a conglomeration of rigid bodies interconnected by springs of varying stiffness and allows the calculation of the acceleration levels at any points within the structure as a function of the geometry and dynamics of the structure. From one perspective, this method can be characterized as the simplest form of the finite element method. For a highly detailed description of this method, reference [4] should be consulted but a synopsis will be presented next.

The analytical technique termed rigid body motion was investigated for a number of reasons. First and foremost, the assumptions associated with this method allow the use of some powerful mathematical techniques such as modal analysis which, in conjunction with engineering dynamics, provide well-formulated equations of motion that are solvable either analytically or numerically. Secondly, this method should provide the most conservative answer of the proposed methods in terms of structural survivability, thus setting an upper bound. Lastly, modeling of the physical system becomes relatively simple and unambiguous, allowing computational algorithms and methods that are not time intensive. For these reasons, this method was investigated. Results generated using this method will be compared with empirical data generated from test programs when available.

A brief technical synopsis of this method and general vibration theory is presented here to facilitate a greater understanding and to present the advantages and limitations of this approach, as seen at this time. A structure, whether it can be considered as a single component with isotropic material properties or as a conglomeration of components that may or may not share similar material properties, has associated with it structural parameters called the natural frequencies with the lowest frequency referred to as the fundamental frequency. These are an inherent property of the structural system only, independent of any external conditions, being a function of the materials, geometry and support system. A natural frequency (or free vibration frequency) is a frequency at which the structure oscillates after an external forcing function, i.e., the initiating

impulse, is removed. Natural frequencies of a structure define the structure's response to external forces; i.e., when the structure is subjected to a broad-frequency acceleration environment such as an impact, the structure will absorb the energy more easily at certain frequencies, the natural frequencies of the system. Consequently, the acceleration response spectrum of the shock environment will have specific values at each natural frequency, the sum of which determines the total response of the structure. These acceleration values at each natural frequency determine the deformations and stresses induced in the structure. In general, the greatest deformation and therefore the largest stresses and strains, occur at the fundamental frequency of the structure. Thus, it is the fundamental frequency that we are interested in because it is associated with the largest peak acceleration values and therefore has the greatest potential for damage. If we can furthermore assume that the fundamental frequency of a real structure is close in magnitude to a similar structure modeled as a rigid-body then this method should be useful.

This idealized assumption that the structure behaves as a rigid body requires that the structural stiffness or rigidity be high, or conversely, the structural damping approach zero. In terms of structural frequencies, rigid body behavior requires that the damped frequency approach the natural frequency. (The damped frequency is defined as the natural frequency of a system with damping.) Mathematically:

$$W_d = W_n \times \sqrt{1 - \zeta^2} \qquad\qquad (2)$$

where
$$\zeta = c / (2\, m\, W_n)$$
W_d = damped frequency
W_n = natural frequency of system with no damping
m = mass
c = damping constant

Thus, when the damping constant c approaches zero, then the damped frequency approaches the natural frequency, as shown in equation 2 above. If we assume a structure composed of a very small number of components, we could determine the natural frequencies of each of these simple components. We could not, in general, determine the natural frequencies of the structure from these individual frequencies since the structural frequencies are functions of the mass, stiffness and damping of each component and the stiffness and damping associated with the interface between components. To analyze anything but an extremely simple model requires a finite element program (FEA) program. So the following assumption is necessary for rigid-body motion. The ratio of the stiffness of each individual component and its interfaces to the stiffness of an equivalent structure of homogeneous material should approach unity where the stiffness is a function of material, material impedance at the interfaces, and structural rigidity. Thus, the damping terms must approach zero or be very small compared to the total mass, as shown in equation 2. For an application to very heavy targets with rigidly welded plates, this assumption is considered reasonable at this time.

Consider a model of an armored vehicle, assuming rigid body motion, as a simple arrangement of two blocks connected by an equivalent spring constant representing the stiffness of the bolted turret/hull interface. This model represents a two-degree-of-freedom system

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requiring the solution of two simultaneous, second order, nonlinear, inertially and elastically coupled equations. This system can be solved two ways, either numerically or analytically. Analytic solutions for this problem were determined [4]; though, in general, there are very few known analytic solutions to nonlinear equations. In order to do this, the nonlinear equations were linearized and then uncoupled using modal analysis techniques. This procedure allows for the relatively simple generation of analytic solutions for various forcing functions where the forcing function chosen is an analytic representation or model of the shock producing impact. The analytic representations under consideration for the forcing function are the Dirac delta function (actually a distribution), a single pulse sine wave, and the function postulated by UDRI when available. (Validation of specific forcing functions for ballistic shock modeling is currently being accomplished by UDRI as part of the overall shock program.) Finally, one of the long term goals would be to solve the system of nonlinear equations numerically for comparison to the linear solutions. At the present time, experimental data is not available to accurately assess the viability of this method but it is believed that this method has its greatest utility in addressing ballistic shock effects in terms of crew casualty predictions in terms of acceleration levels and structural failure of the hull/turret interface. Future work required is to determine the viability of this method by correlating to experimental data and, if warranted, incorporating the software into a current vulnerability methodology.

3.2.2 SHORTEST PATH METHOD

A primary reason for investigating the shortest path method is the apparent lack of intensive manpower and computer resource requirements associated with such a method. The idea here is to track ballistic shock attenuation along the shortest straight path from an initiation point (impact point) to various predefined response points, thus eliminating the need for detailed finite element models. The response points of interest would be mounting points on a vehicle structure for "shock sensitive" components. This follows closely with Walbert's proposal [1] and is similar to work by Barrett [5] where shock requirements for Viking Lander components were developed. This method is broken down into three separate subareas that will be discussed below. The three areas are algorithm development, experimental support, and visualization.

3.2.2.1 ALGORITHM DEVELOPMENT

It is by no means a simple task to develop an algorithm for ballistic shock attenuation through armored vehicle structures. Several simplifying assumptions had to be made and many factors had to be considered. To simplify the problem, at least initially, only the first shock to reach a response point was to be considered. This was done to eliminate the constructive and destructive interference effects of reflected waves. Along with this simplification came the assumption that the first shock would be the most capable of causing damage. It is interesting to see if such an approach would result in the calculation of acceleration levels that were comparable to experimental data.

The form of the algorithm developed must account for several factors such as material properties, armor thickness, geometry of joined plates, loading functions, decay rate, etc. Some

of the inputs for these items will be empirically based while others will be strictly analytical. The effect of geometry between joined armor plates has been investigated, through finite element analysis and experimentation, and algorithms for attenuation (knockdown factor) based on plate angles has been developed [6]. This effort is discussed in more detail in section 3.2.2.2. At the present time, all of the empirical coefficients for the algorithm have not been determined; but it is believed that sufficient experimental data exist such that an initial set can now be developed. Currently, the output of the algorithm is in terms of acceleration. It is planned that the algorithm be updated to provide acceleration time histories at response points that could be converted to shock response spectra (SRS). The SRS capability will become important when the problem of individual component failures/degradations is addressed (Part 3 of the overall program).

3.2.2.2 EXPERIMENTAL EFFORT

The experimental work to be discussed here is work that only supported the investigation of the effect of angle variation between welded armor plates for the shortest path portion of the over-all shock program. (Experimental data that supports all phases of the program will be discussed later in a separate section.) There were three simple questions that this experimental effort was to answer. These questions were:

1. Is there an effect on shock attenuation due to angle variation between welded plates?

2. If the answer to the question above is yes, then what is the relationship between attenuation and the angle at which the plates are connected?

3. Is the effect on attenuation due to angle variation constant over a range of plate materials and impact conditions?

The approach taken was to start experimentation with flat plates to obtain baseline acceleration levels and then to proceed to plates connected at various angles to determine attenuation due to geometry changes. Distance between impact and response points was held constant for all plates. All plates were 0.5 inches thick and were made of either 5083 aluminum or mild steel. Including the flat plates there were five different aluminum plates and seven different mild steel plates. Impact conditions remained in the elastic range to conserve target materials. The impacting mechanism was a 1 inch diameter steel ball bearing dropped from three different heights using a two wire pendulum. In all, 201 experiments were conducted to gather what was felt to be sufficient data for an initial attempt at formulating an attenuation algorithm for welded angled plate connections.

Final results of this effort show that there is an effect due to angle variation between plates. Attenuation functions were developed as functions of angle using regression analysis. The experimentally based functions agreed fairly well with functions based on finite element calculations with the finite element based functions being slightly more conservative at calculating attenuation. All of the functions were of the same basic form and contained similar coefficients, but were still different enough as to leave the question concerning the consistency of attenuation over a range of materials and loading conditions unresolved. Until more experimental data can be collected it is proposed that the more conservative finite element based attenuation

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function be implemented in the shortest path method. This function, which is a multiplicative factor in the shortest path algorithm, is as follows:

$$A_f = 1.0 - 0.2\alpha + 0.08\alpha^2$$

where A_f = Attenuation Factor

α = the plate angle in radians and is measured as π radians minus the angle subtended by the two plates.

3.2.2.3 VISUALIZATION TOOL

It was felt that having a tool to visualize the developed algorithm(s) would be instrumental to the shortest path method. In particular, sensitivity analyses for various parameters could be conducted that would help direct future efforts. Thus, a task order contract was initiated with the SURVICE Engineering Company to develop a visualization software testbed that would accept the ARL developed algorithms and that would use geometry generated by BRL-CAD. This software overlays a simplified vehicle geometry over internal components so that one can look at the shock environment around specific components. Ultimately, much of the programming effort that was utilized for this tool will pay dividends when ballistic shock is incorporated into the MUVES environment as a damage-producing mechanism.

3.2.3 BLACK BOX APPROACH

Given that we can assume a cause and effect relationship between structural response and observed damage when a structure is subjected to a ballistic shock input, one simple approach would be to model the structure as a "black box" and treat the entire ballistic event as a process by which energy is put into the "black box" with a deformed/damaged structure being the output. One conceptual problem with an approach such as this is that the structure "is" the "black box" which means its properties must be characterized and the structure "is", in a different state, also the output or product of the process. As was stated before, for this approach to be viable the structure must be characterized - if possible idealized - so that the process of taking the structure from the undamaged state to the damaged state is mathematically tractable.   It is often possible to characterize the input and output of a ballistic shock event, the input being the energy imparted to the structure by the incoming munition and the output being the damage state of the structure as the event ends. The challenge of the "black box" approach lies in accurately modeling the process or mapping that connects the characterization of the structure in its undamaged state to the characterization of the structure in its damaged state. The mathematical construct usually used to map an input to an output is a transfer function. Transfer functions can be formed from differential equations which characterize a process. As an initial step, the ballistic shock event can be thought of as an energy absorbing process by the structure. Given a sufficient amount of energy input, the energy the structure can absorb can be dispersed in two ways. The first is the absorbed energy

that produces structural motion in the form of vibratory motion in one or more of its natural frequencies. The second is the energy associated with the permanent deformation of the structure. As the structure is permanently deformed, heat is generated. This heat and the energy it represents is lost to the surroundings. So the total process we are trying to capture is an influx of energy which is processed by a structure of an initial geometry and character to arrive at an end state which is the structure with a changed geometry and perhaps a changed character. As was stated earlier, differential equations which can be stated as transfer functions are thought to be a good starting point for this approach to the analysis of ballistic shock-caused damage. The initial choice will be a differential equation based on the wave character of both the vibration of the overall structure and the stress propagation associated with the structural deformation process. Future formulations will attempt to incorporate the internal storage of strain energy, the inefficiencies associated with the energy transfers occurring throughout the process, and attempts to deal with the details of the structural geometry and its effect on the end state.

3.2.4 EXPERIMENTAL EFFORTS

As was stated in BRL-MR-3930 by Walbert [1], one of the initial steps in quantifying the effect of ballistic shock is to measure the response of simple structures as a starting point in an attempt to approximate the response of more complex structures. Initial experimentation in this area was carried out by impacting flat and bent plates composed of aluminum and steel with a steel ball bearing and recording the response using accelerometers attached to the plates [6]. Moving up the ladder of complexity, the second series of experiments was to subject the simplest combat vehicle configuration available to shock loading by attaching a small spherical charge to an exterior structural member and detonating it. Using acceleration as the parameter of interest, the response of the vehicle was recorded using accelerometers placed in patterns tracing straight lines radially outward from the point of impact. Two vehicles were available candidates for the experimentation. The first was the M113 armored personnel carrier. This is a box-like light combat vehicle constructed from aluminum plates. Preliminary analysis of the acceleration data gathered has shown that calculations using the velocity of sound in the material as the observable wave speed of propagation are correct within the ability of the data acquisition system's ability to record an accurate event start time. Response data recorded from the accelerometers attached to the M113 are currently being analyzed to reveal the shock and power spectra produced. The second candidate was the BMP armored personnel carrier. This vehicle is also box-like, but somewhat longer than the M113 and is constructed from steel plates. It also has many straight line wave propagation paths across flat plates from which to gather field data. Experimentation on the BMP has been conducted and the data gathered is currently under analysis. It is envisioned that the field data gathered during this experimentation will validate the computational efforts outlined in this report, or if validation is not possible, perhaps point to alternative paths of investigation.

4. SUMMARY

An overview of the current work for the shock program initiated at ARL has been given along with the associated rationale and technical objectives. The various avenues of research under the umbrella of the shock program have also been presented in a cursory manner. At this time it is premature to suggest that one of the various methods has significant merit, or even more merit than other methods. That assessment has to be made at a later date after further methodology development has occurred and more empirical evidence has been analyzed. A program schedule is presented next.

BALLISTIC SHOCK PROGRAM MILESTONES AND OBJECTIVES

Objective	Responsibility	Date	Risk
1) Characterize Loading Functions	UDRI	JUN 94	Medium
2) Develop Shock Analysis Tools			
a. Analytical - Shortest Path	BVLD	MAR 94	Low
Rigid Body	BVLD	MAR 94	Medium
Black Box	BVLD	FY95	High
FE Anaysis	UDRI	JUN 94	Medium
b. Experimental - M113 Tests	BVLD/WTD	FY94	Low
BMP-2 Tests	BVLD/WTD	FY94	Low
3) Assess Shock Tools Qualitatively for Simple Structures	BVLD	FY95	Low
4) Qualitative Damage Rules	BVLD	FY95	Medium
5) Implement Damage Rules in a Vulnerability Suite	BVLD	FY95	Medium
6) Develop Component Shock Criteria	BVLD	FY95	High
7) Determine Quantitative Shock Response of Real Structures	BVLD	FY96	High
8) Assess Shock Tools Quantitatively	BVLD	FY96	High
9) Implement Quantitative Shock Tools in a Vulnerability Suite	BVLD	FY97	High

5. REFERENCES

1. Walbert, J.N., "A Proposed Method for Incorporating Ballistic Shock Effects in Vulnerability/Lethality Analyses," Memorandum Report BRL-MR-3930, August 1991.

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